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Hydrogen Deployment System Modeling Environment (HyDS ME) Documentation

Milestone Report FY 2006

Keith Parks
National Renewable Energy Laboratory

Milestone Report
NREL/MP-560-40763
November 2006

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Keith Parks
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Prepared under Task No. HY65.2100

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Introduction

The Hydrogen Deployment System Modeling Environment (HyDS ME) considers hydrogen infrastructure at the regional level. The user interface is shown in Figure 1. The unique elements of this model include:

- Regional perspective with granularity down to the urbanized area.
- Geographic Information Systems (GIS) platform to consider spatial relationships between markets.
- Competes different production and delivery technologies for least-cost solution.

This report introduces the model, assumptions, and basic operation. Initial results are presented at the end of the document.

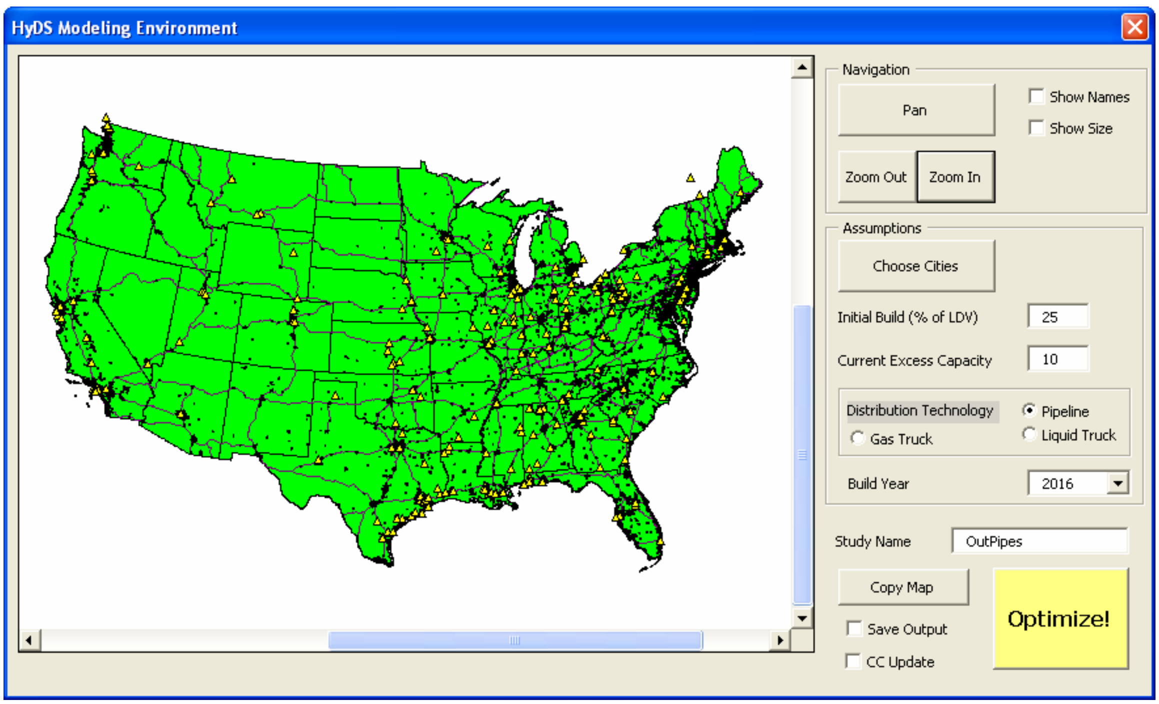

Figure 1 – HyDS ME User Interface

Overview

The HyDS Modeling Environment, or HyDS ME, is a GIS-based infrastructure optimization model. The model combines existing cash flow models, GIS capability, and an optimization routine to determine the layout of a least-cost infrastructure. The user chooses the region, a forecasted year, a desired hydrogen vehicle penetration, a forecasted natural gas price, and other options. HYDS ME then determines the optimal least-cost infrastructure (Figure 2).

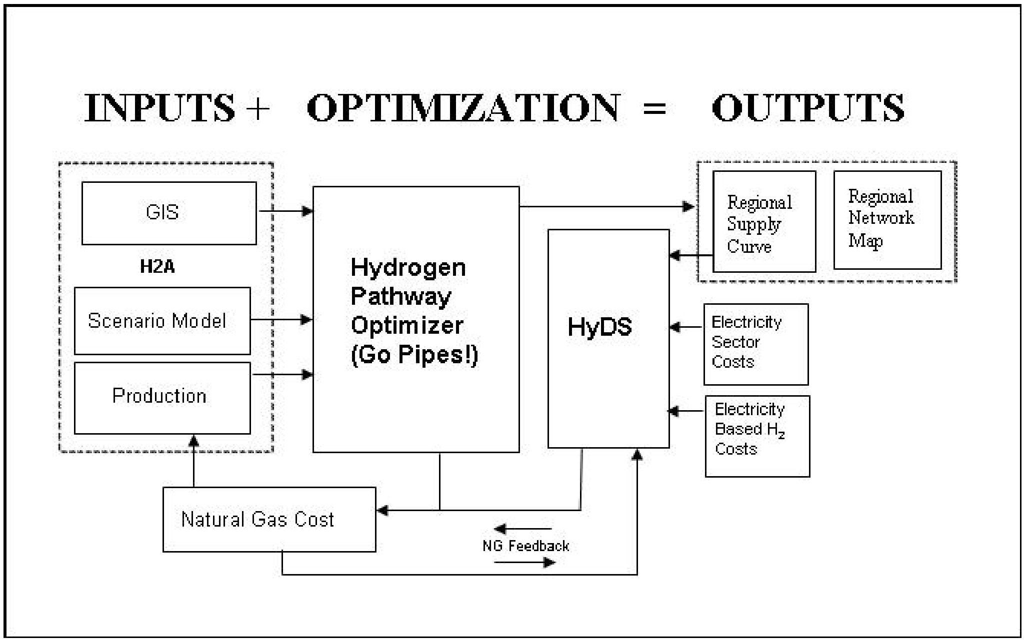

Figure 2 – HyDS ME Operations Schematic

A regional supply curve is output along with a corresponding map of the infrastructure (Figures 3 and 4). The map illustrates the spatial relationship of the hydrogen infrastructure while the supply curve identifies the cost impact. These outputs are described at length later in this document.

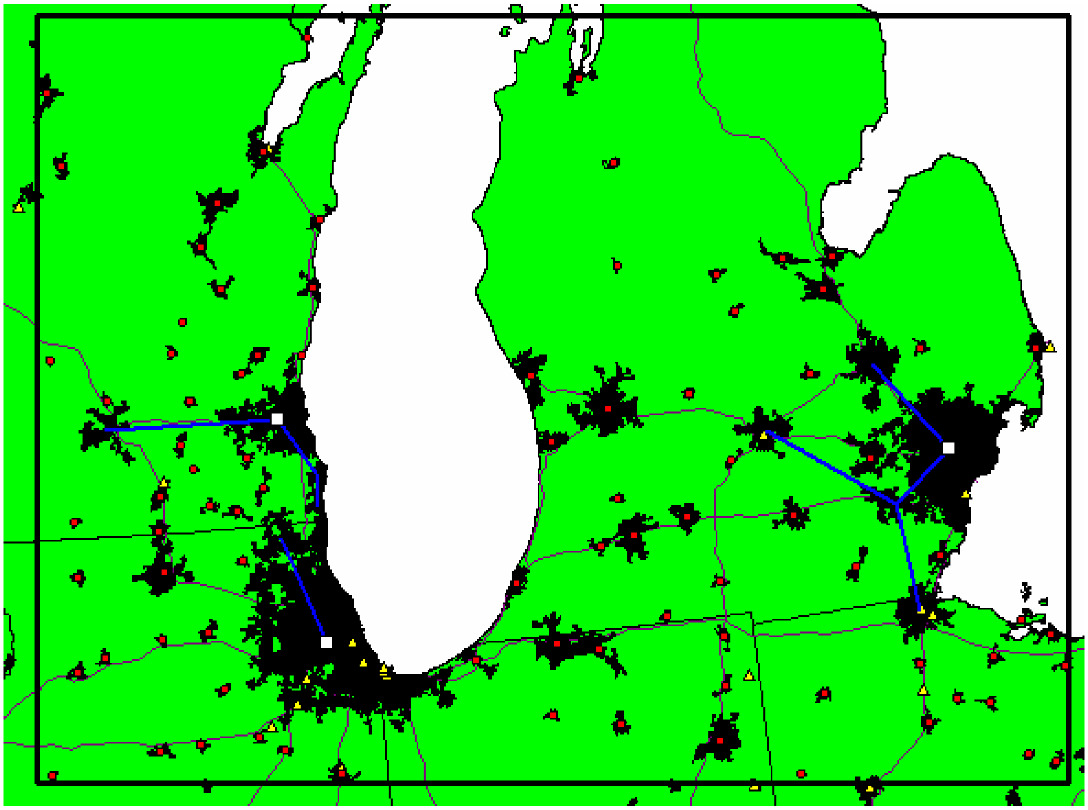

Figure 3 – Infrastructure Map

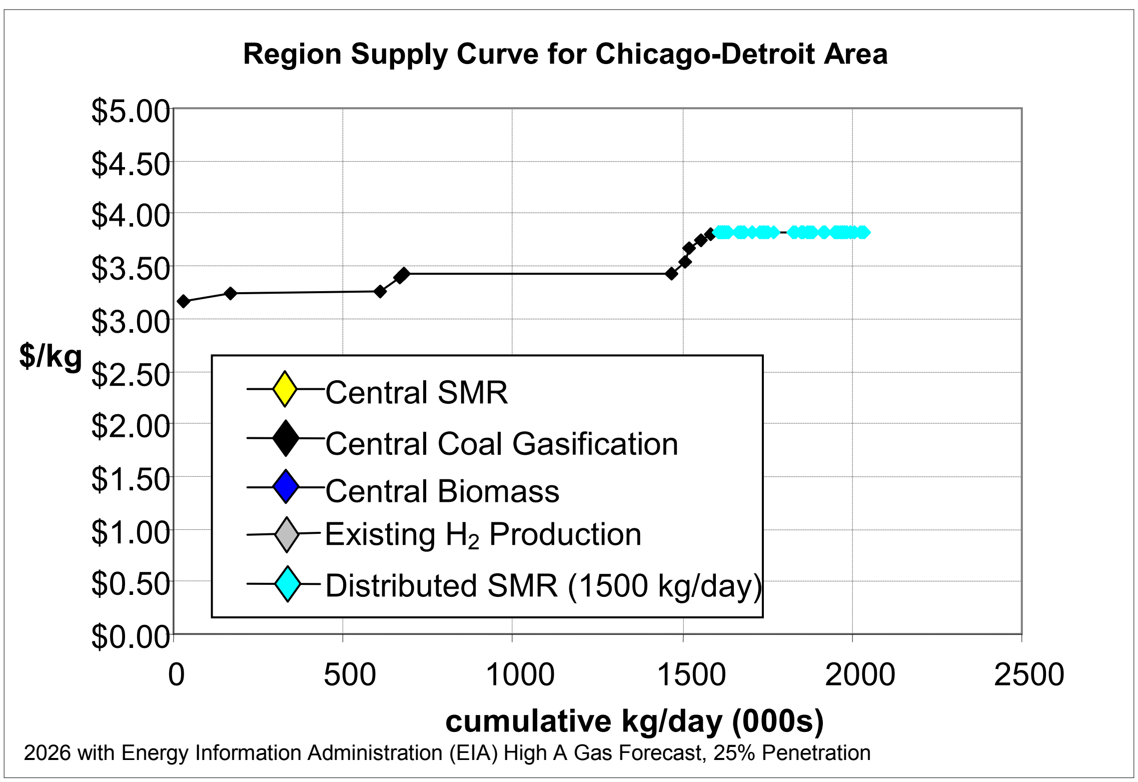

Figure 4 – Regional Supply Curve

Methodology

HyDS ME uses a modified minimum spanning tree algorithm to compete different production and delivery technologies to determine a least-cost solution. This algorithm falls in the optimization realm of graph theory. A graph *V* is a set of nodes *N* and edges *E*. Graphically, edges connect nodes (Figure 5). By assigning a cost to each edge, a defined problem emerges with regard to connecting the nodes at least cost. A minimum spanning tree is a special subset of edges that connect all the nodes within the graph at a least cost. That is, a minimum spanning tree answers the question: "how can one connect all the dots (nodes) with least effort, reflected as least cost?"

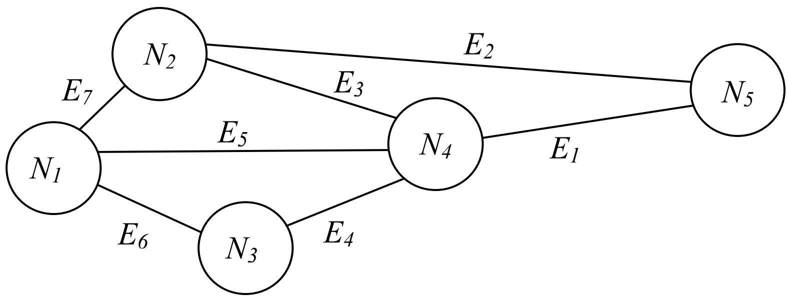

Figure 5 – A graph (*V*) Consists of Nodes (*N*) and Edges (*E*)

In the hydrogen infrastructure deployment context, urban areas are nodes while the various modes of delivering hydrogen are edges. In essence, there are three primary pathways or choices associated with each urban area. It can serve its load through (a) its own distributed hydrogen generation, (b) its own centralized hydrogen generation, or (c) piggybacking onto a neighboring community's centralized hydrogen production. There are many options for production, transport, and delivery associated each of these three choices. HyDS ME assesses these options to determine the least cost city and its choice for production, transport, and delivery. All other cities' costs are updated to reflect this choice. The model works iteratively through all the cities within a specified region, allowing for regional clusters to develop, leveraging the demands of nearby larger cities, and creating an interdependent delivery network.

Table 1 lists the production, transport, and delivery components considered for hydrogen pathway optimization within the HyDS ME. Component costs are derived from the H2A Production spreadsheets and the H2A Scenario Model. These costs are further explained in the following section.

Table 1 – Production, Transport, and Delivery Infrastructure Available within the HyDS ME

Production, Transport, and Delivery Technologies

Central Production	*Distributed Production*	*Transport & Delivery**
SMR w/out CCS	SMR (100 kg/day)	Compressed Gas Truck
SMR w/ CCS	SMR (1500 kg/day)	Liquid Truck
Coal Gasification w/out CCS	Electrolysis (100 kg/day)	Pipeline
Coal Gasification w/ CCS	Electrolysis (1500 kg/day)	
Biomass		
Wind		
Wind w/ Co-Product		
Nuclear Hi Temp Etrol		
Nuclear Sulfur-Iodine		

* Transport and Delivery are further divided into component parts

Transport and Delivery Components

Compressed Gas Truck	*Liquid Truck*	*Pipelines*
Truck & Trailer	Truck & Trailer	Transport Pipeline
Compressor	Liquefier	Distribution Pipelines
Terminal	Terminal	Compressor
Station	Station	Station

Note: "SMR" refers to Steam Methane Reforming; "CCS" refers to Carbon Capture and Sequestration.

Pathway Costs

The complete pathway cost is the sum of the production, transport, and delivery costs. Figure 6 illustrates the various HyDS ME pathways. The model considers each step of the pathway, taking into account different technologies and their respective scale economies. Production refers to producing hydrogen and enabling the hydrogen to be transported. Transport refers to the transport of hydrogen from the production facility to the city-gate. Finally, delivery, or distribution, considers the transport of hydrogen from the city-gate to the station.

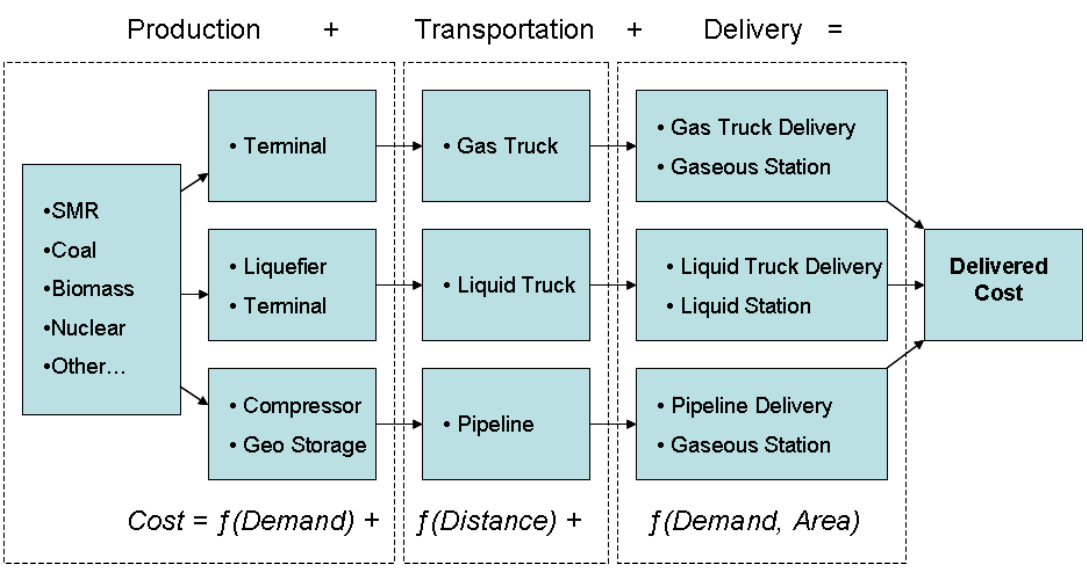

Figure 6 – Pathway Costs

Production

Production cost is the sum of the cost of producing hydrogen and the cost of enabling the hydrogen to be transported. For central production, enabling technology is sized relative to the production facility and is assumed to be proximal to the production facility. Several assumptions regarding the cost of producing and enabling hydrogen are made.

Central Production: Fixed and Variable Costs

The cost of producing hydrogen is the sum of the fixed and variable production costs (Figure 7), both derived from the H2A Production spreadsheets. These spreadsheets forecast the unit cost (expressed in units of output, $/kg) necessary to achieve a specified return on investment. As the return is assumed to incorporate profit, this unit cost is referred to as the *profited cost*. For use in HyDS ME, the profited cost is broken into fixed and variable components. Fixed costs are the sum of the capital and fixed operations and maintenance costs. Variables costs are the sum of feedstock and variable operating costs.

Economies of scale affect fixed cost as a function of plant capacity but are bounded by minimum and maximum capacities. Since H2A evaluates many technologies at a single, discrete capacity, its framework does not inherently consider economies of scale. HyDS ME assumes the fixed cost for most technologies varies by an exponential function of capacity, where the exponent is fixed at 0.6. The exception to this approach is steam methane reforming (SMR). SMR has three data points (15 ton, 30 ton, 340 ton) within the H2A framework. From these three points, the model derives a least-squares exponential function[1].

Minimum and maximum capacities of plants are enforced. The limitations are intended to preserve real limits on the expected deployable size of the technologies. In Figure 7, minimum capacity is enforced by pricing the technology at an extraordinary cost (1). The maximum capacity is enforced by eliminating economies of scale (2). Without this limitation, scale economies would extend to unrealistically large facilities. The model assumes variable costs specific to each technology will remain the same regardless of scale[2].

[1] These assumptions are consistent with conversations and correspondence with researchers in hydrogen technology validation and other transition infrastructure modelers.
[2] Again, these assumptions are consistent with conversations and correspondence with researchers in hydrogen technology validation and other transition infrastructure modelers.

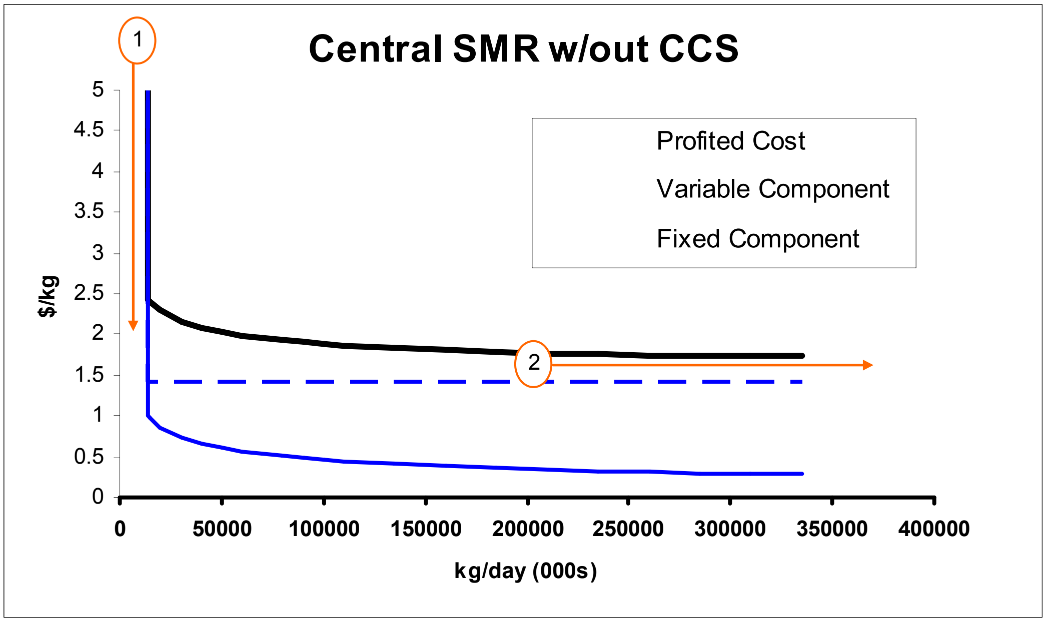

Figure 7 – Total Cost is the Sum of Fixed and Variable Costs

Operationally, the H2A Production spreadsheets are directly linked to HyDS ME, facilitating sensitivity runs. For example, the assumed feedstock prices are a major input to the H2A Production spreadsheets. To simplify sensitivity runs, natural gas prices are an input to HyDS ME[3]. Since the model links to H2A Production, the new price is reflected in HyDS ME in the form of higher variable costs for SMR.

Enabling Transport and Delivery

The model considers some components (liquefiers, compressors, and terminals) as central technologies. These technologies enable the transport of hydrogen from production into the delivery system. The model considers the sharing of these potentially significant costs. A cluster of cities may share a central enabling technology; thereby gaining scale economies, much the same way cities gain scale from implementing central production technology. Therefore, as more and more cities link to a central production facility, they experience gains from scale economies in production as well as in the liquefier, terminal, and/or compressor.

Enabling technology costs are derived from the H2A Scenario Model. The methodology is discussed later in the delivery section of this report.

Distributed Production versus Central Production

Production technology comes in two basic types: central and distributed. These types balance production scale economies with transport and delivery costs. Because distributed technologies produce hydrogen on site, they incur no transport and delivery costs. However, due to their small capacities, they also cannot take advantage of

[3] There are placeholders in the HyDS ME for prices of other feedstocks such as coal and electricity. These can be added but currently are not active due to time constraints.

significant scale economies that could reduce their production fixed unit costs. Conversely, central technologies can reduce the fixed component of production costs through increasing scale, but incur sometimes substantial costs to transport hydrogen to the dispensing site.

Distributed production is assumed to be at either 1500 kg/day or 100 kg/day. The two technologies available are SMR and electrolysis. The costs for these technologies are taken directly from the H2A Production spreadsheets.

HyDS ME competes central versus distributed technologies. As demand increases (associated with larger penetration), central production gains scale economies thereby reducing production costs. Eventually, these costs drop enough so that the combined cost of production, transport, and delivery becomes less than the production cost of distributed technologies. Until such scale is feasible and economic, the model selects distributed technology, opting for the smaller, less efficient production technology but avoiding the additional costs of transport and delivery.

Leveraging Central Production

One way a smaller city can lower its delivered cost is by leveraging the centralized production capability of a neighboring community. By itself, the smaller community may opt for a distributed technology. With a neighboring larger market, however, the community has the option to link to the neighbor's production center and incur the additional cost of transport and delivery. Other communities may also join, creating a transport network extending out from the central plant. Eventually, as the distribution system increases in area, small communities or communities distant from the central facility will have transport and delivery costs that overwhelm the production scale economies. These communities will forgo the network in favor of distributed technology.

Geographically, this leveraging opportunity creates, with sufficient demand, a hybrid hydrogen infrastructure incorporating both central and distributed production. Figure 8 depicts a representation of the Chicago-Detroit region assuming a uniform penetration of fuel cell vehicles to 15% of total light duty vehicle stock. The dark blue lines connecting Chicago and Detroit with the outlying urban areas represent hydrogen pipelines. The light blue shaded areas emphasize the extent of the pipeline coverage. Areas outside the pipeline network chose to install distributed technologies to avoid the increasing cost of transport and delivery. Thus, a geographic break is anticipated with regard to central versus distributed technology.

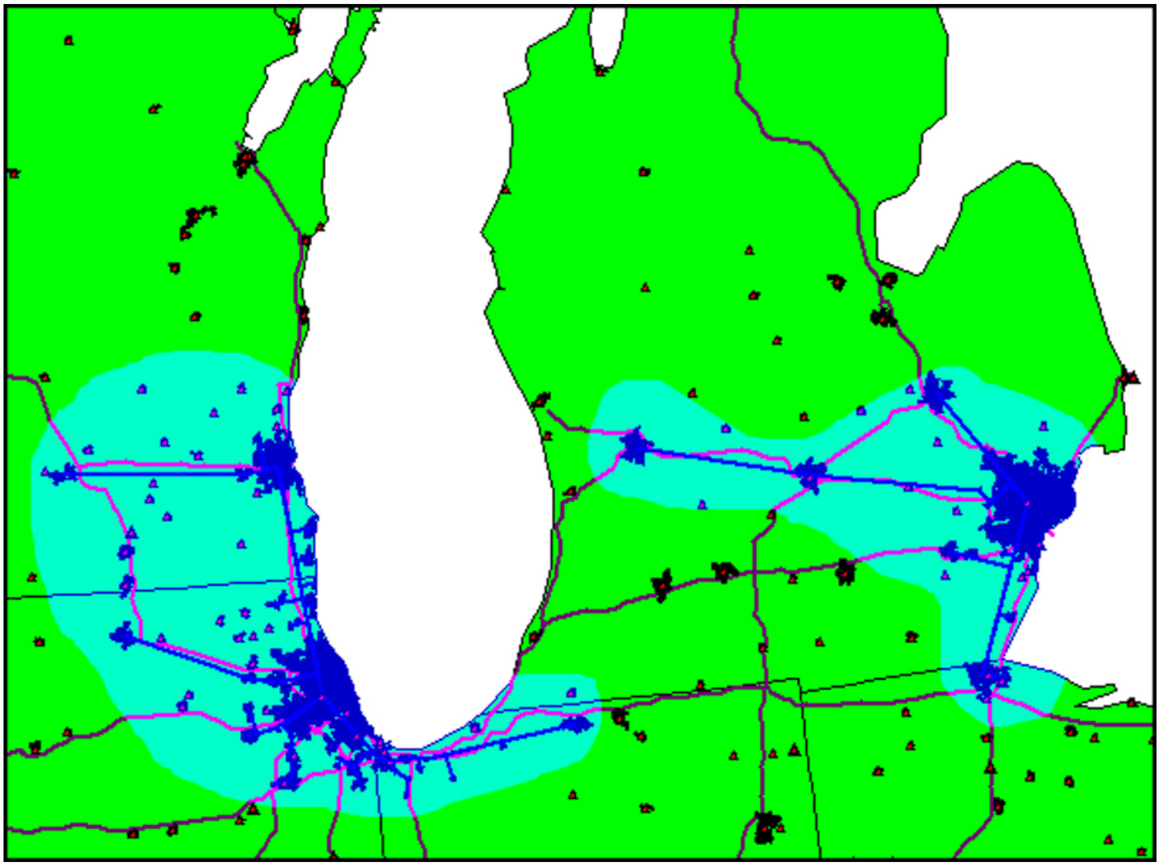

Figure 8 – Central Versus Distributed Interface

Transport

Transport refers to the transport of hydrogen from the production facility to the city-gate. Transport costs are derived from the H2A Scenario Model.

Gas and Liquid Truck

For truck delivery, transport costs largely depend on distance. In order to model this relationship, the H2A Scenario model was run for several distances to the city gate (zero miles, thirty miles, and 100 miles) while also varying the level of hydrogen demand. The additional distance, reflected in additional transit time, not only drives nominal additional labor and diesel costs, but also requires more truck/trailers due to lower utilization of the delivery infrastructure. The model assumes that additional hydrogen demand does not affect truck transport costs. A linear equation, graphed separately for gas and liquid transport in Figure 9, was derived to explain the truck/trailer transport costs.

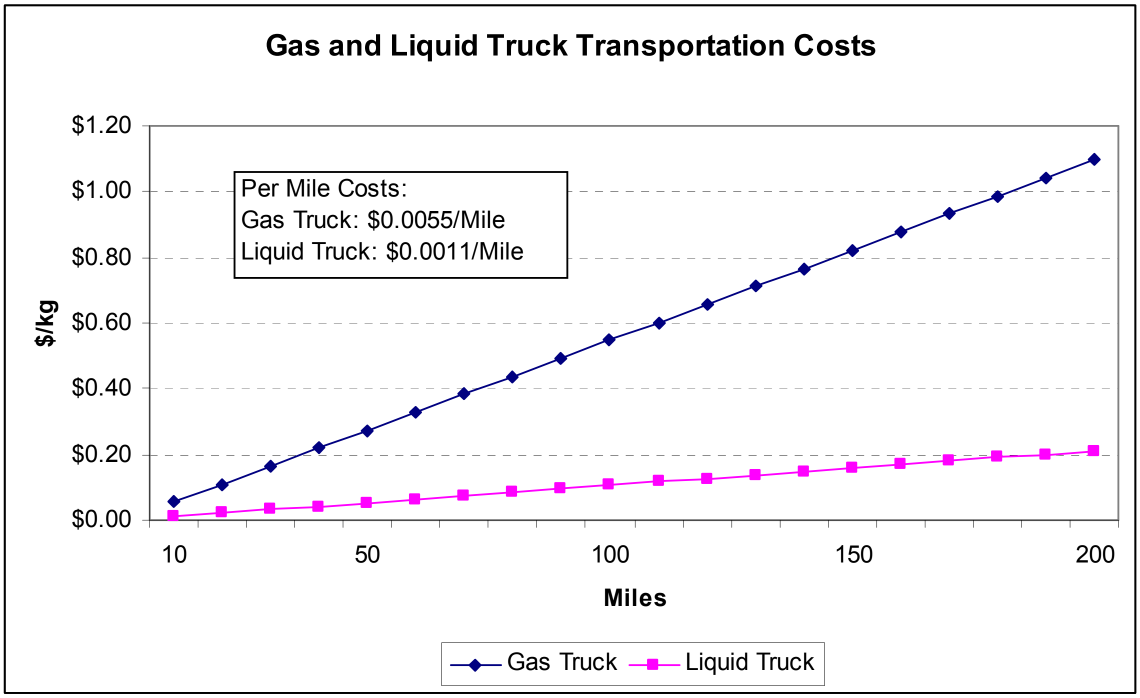

Figure 9 – Gas and Liquid Truck/Trailer Transport Costs

Pipelines

The pipeline component costs were extracted from the H2A Scenario Model to create a stand-alone transport pipeline cost model. Since the relationship between demand, distance, and cost is not a simple linear one, more sample points were necessary to reduce the pipeline model to a more simple form. Crystal Ball[4] was used to create 10,000 sample points. A least-squares regression was performed in this sample set (Figure 10). Consistent with H2A Scenario Model assumptions, pipeline transport costs are most sensitive to hydrogen demand and distance. Distance is an obvious cost component (more distance requires more pipe). Increased demand drives larger pipeline diameters. If larger pipelines can be justified, then costs are amortized over substantially more units of hydrogen, thereby driving down the unit cost of transport. Regardless, transport costs are relatively small when compared to production and delivery.

[4] An Excel add-in normally used for Monte Carlo probability simulation.

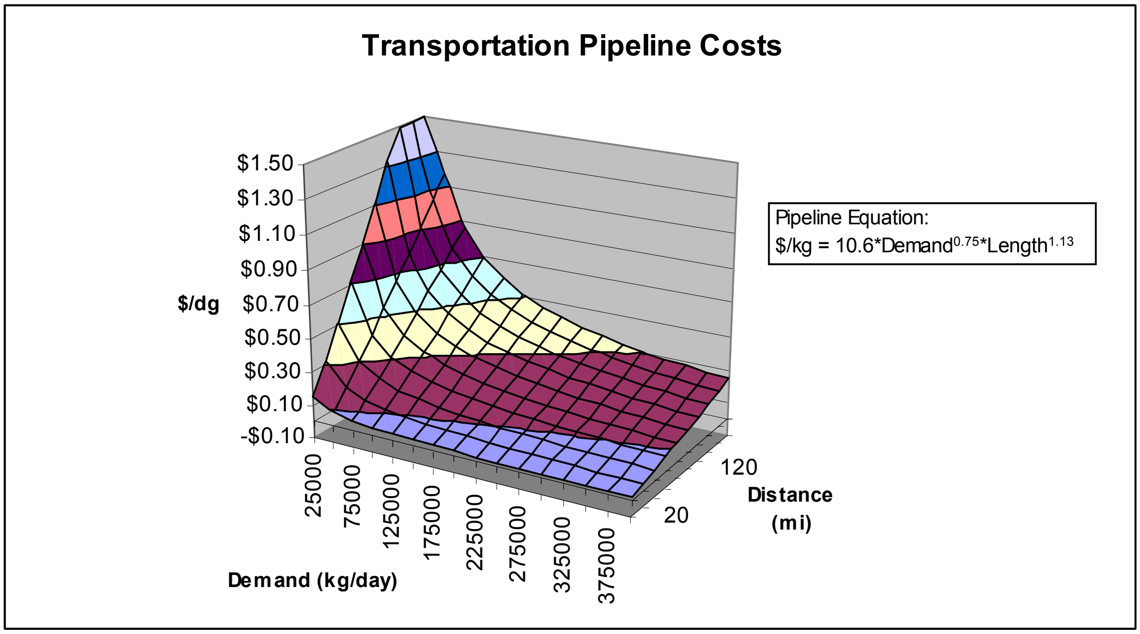

Figure 10 – Pipeline Transport Costs

Delivery

Delivery considers the transport of hydrogen from the city gate to the station. For gas and liquid truck delivery, these costs include the truck and trailer, station, and dispensing costs. For pipeline delivery, the costs include main and feeder pipelines along with the station and dispensing costs. Every urban area must bear the cost of delivery on its own. Delivery costs depend on the city size and the demand. Small communities may have large costs due to the small market while large cities may suffer from their large urban expanse. Since delivery costs are derived from the H2A Scenario Model, the HyDS ME treatment of delivery inherits all the assumptions embedded in that model.

Delivery Costs

The H2A Scenario Model was used to estimate delivery costs. Component costs were first recorded for several hundred model runs. An equation was then fit to each sample set via least-squares regression using demand and city area as the determinants of cost. The functional form of the resulting equation varies by component (Table 2).

Table 2 – H2A Scenario Model Reduced Form Delivery Cost Equations by Component

Gas Truck (100 kg/day)			**Liquid Truck (1500 kg/day)**			**Pipelines (1500 kg/day)**		
Station	*A*		*Station*	*A*		*Station*	*A*	
A		2.38	A		0.57	A		0.86
Terminal	*A*LN(X)^B*		*Terminal*	*A+B*(1/X)*		*Compressor*	*A*LN(X)^B*	
A		4015.40	A		0.24	A		278.31
B		-3.36	B		2927.23	B		-3.03
Delivery	$A+B(1/X)+C(Y^{1/2})$		*Liquifier*	*A*LN(X)^B*		*Pipelines*		
A		1.50	A		98502.51	A		8.55
B		299.11	B		-4.46	B		0.06
C		0.02	*Delivery*	$A+B(1/X)+C(Y^{1/2})$		C		-1.72
			A		0.09	D		1.03
			B		231.42	*GeoStorage*	*A*LN(X)^B*	
X = Demand			C		0.00	A		6501.56
Y = City Area						B		-4.39

Values of R^2, a measure of the goodness of the regression fit to the original data, are routinely 0.98 or higher. The regression fit declines somewhat at low demands for very small city areas and high demands for very large city areas. Given the high R^2, NREL is confident that these reduced form equations are an accurate and appropriate reduction of the H2A Scenario Model for the most likely scenarios where central technologies would be applied.

As an example, the H2A Scenario Model sample set and the resulting reduced form equation fit are displayed in Figure 11 for pipeline delivery costs in several large urban areas in relation to hydrogen demand. The simplified equation (in blue) maps closely to the values reported in the H2A Scenario Model (in purple). Delivery costs, in both H2A and reduced form, exhibit similar behavior across metropolitan areas. For example, for the NYC Metro Area, intra-city pipeline costs drop initially with the number of vehicles served, but then flatten out and rise slightly as demand further increases. The pipeline costs associated with NYC are substantially higher than those for Seattle due mostly to NYC's larger city aerial extent and higher concentration of vehicles.

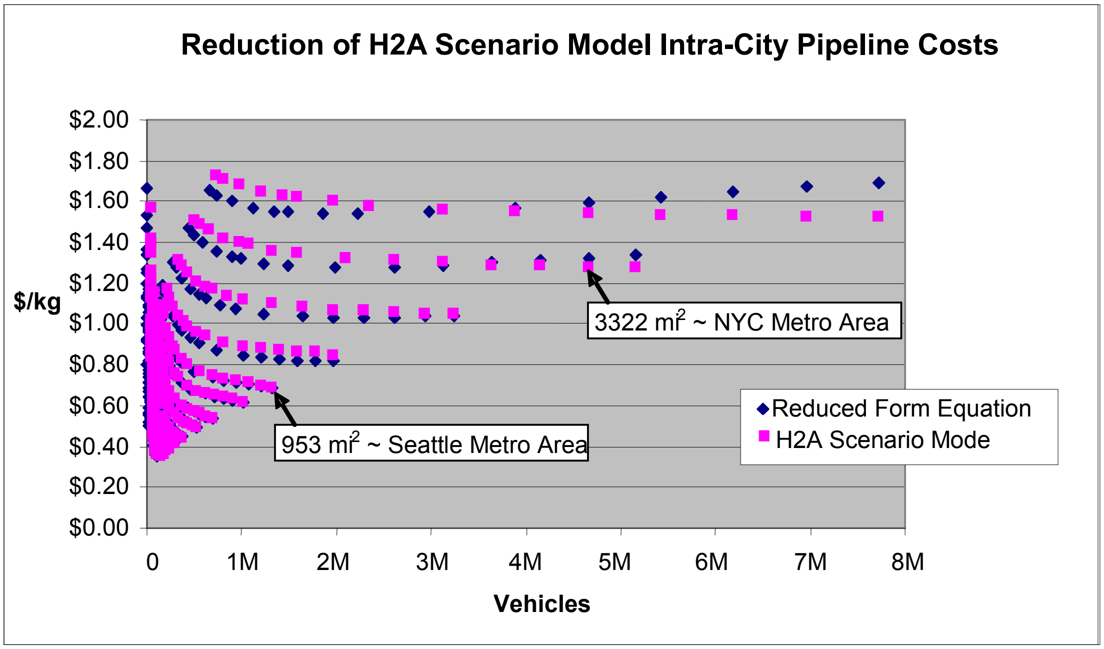

Figure 11 – Intra-city Pipeline Assumptions

Hydrogen Demands

To calculate hydrogen demands, HyDS ME uses GIS information to spatially represent the distribution of vehicles across the U.S. The Census Bureau's Urban Area definition is used to define city boundaries. An Urban Area (UA) is defined as a core census block group having a population density of 1,000 people per square mile plus all contiguous areas with more than 500 people per square mile. Further, Urban Areas have populations of 50,000 or greater. Urban Clusters (UC) have the same density requirements but are limited to populations under 50,000.[5] HyDS ME combines the Census UA and UC definitions and enforces a lower bound of 10,000 (i.e., a UA/UC in HyDS ME has a population greater that 10,000).

The Census reports, by census block, average vehicles per household and the number of households. Consider each UA_k. The number of household vehicles within UA_k can be calculated as follows:

$$Vehicles_k = \sum_{i}^{i \in UA_k} AverageVehiclesPerHousehold_i * NumberOfHouseholds_i$$

for all census blocks i with UA_k.

Using this approach, the total number of household vehicles in the urban areas definition, corresponding to the red areas in Figure 12, is 110 million vehicles. The total number of household vehicles for the entire United States, represented by the shades of blue in the figure, is 182 million vehicles. Therefore, there are 72 million vehicles, or 40% of the

[5] US Census Bureau Website;
Census 2000 Urban and Rural Classification; http://www.census.gov/geo/www/ua/ua_2k.html

total vehicles population, that do not reside at households included in the UA/UC definition.

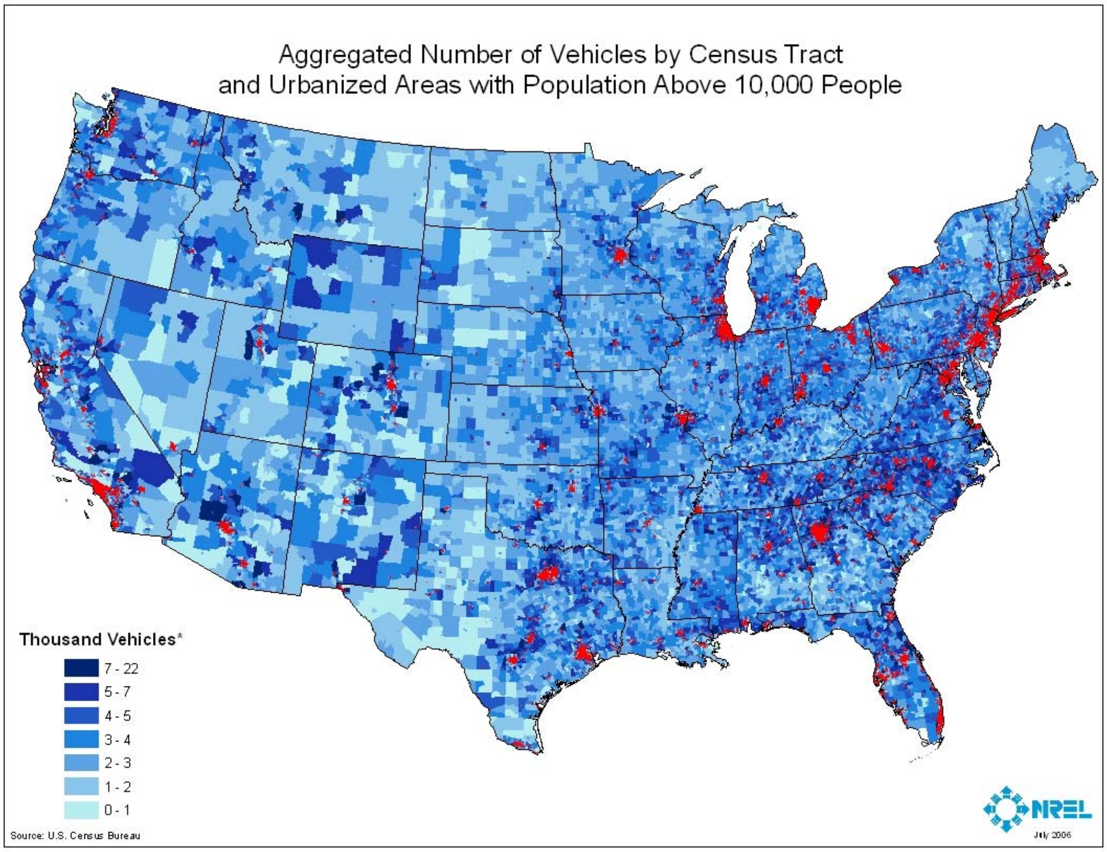

Figure 12 – Vehicle Population Overlaid with the UA/UC City Definition
Note: Urban Areas with populations above 10,000 are shown in red. Vehicle population is shown as shades of blue.

Household vehicles account for most, but not all, vehicles. Commercial and government vehicles are excluded from these Census-based figures. Alternative sources of data verify that the Census calculation undercounts the total number of vehicles (Table 3). The Energy Information Administration (EIA) data is based on the Department of Transportation's *2001 National Household Travel Survey*. The EIA data, reflecting a survey performed by household, are relatively close (within 6%) to the Census information.

Table 3 – Reported National Vehicle Data by Source

Data Source	2000	% Difference
Census Bureau	178,390,043	
Energy Information Agency [2]	187,944,000	5.4
Bureau of Transportation Statistics [1]	212,706,399	19.2

[1]Passenger Cars plus other 2-axel 4-wheeled vehicles for 2000

[2]2001 reported data reduced by 1.6% (prevailing 10-yr average)

Sources:

Census - 2000 Census (2000)

BTS - National Transportation Statistics 2005 (December 2005)

EIA - Household Vehicles Energy Use: Latest Data & Trends (2001)

The Bureau of Transportation Statistics (BTS) collects data on all registered vehicles by state. For our purposes, registered vehicles comprise all road-worthy vehicles including private, commercial, and government vehicles. The difference between the BTS and Census totals, 19.2% on a national basis, reflects the Census' lack of inclusion of non-household vehicles. Assuming non-household vehicles are distributed proportionally by the household vehicle population, the Census UA/UC vehicle estimates are increased by this factor for use in HyDS ME to reflect the inclusion of non-household vehicles (Table 4).

Table 4 – Most Populous Urban Areas and Vehicle Counts

Urban Area	State	Population	Census - Orig	Census - Mod
New York--Newark	NY	17,340,042	6,983,737	8,327,178
Los Angeles--Long Beach--Santa Ana	CA	11,784,473	6,265,225	7,470,448
Chicago	IL	8,299,353	4,278,249	5,101,243
Philadelphia	PA-DE	5,142,385	2,675,069	3,189,664
Miami	FL	4,901,994	2,666,928	3,179,957
Detroit	MI	3,900,539	2,410,285	2,873,944
Dallas--Fort Worth--Arlington	TX	4,140,851	2,384,910	2,843,688
Washington	DC	3,936,201	2,268,652	2,705,066
Boston	MA	4,014,865	2,147,915	2,561,104
Houston	TX	3,819,632	2,039,996	2,432,423

Note: "Census – Orig" refers to original Census data (household vehicles only). "Census – Mod" values result from inflating the original by a constant factor to reflect the addition of non-household vehicles.

User Guide for Operating the HyDS ME

HyDS ME combines Microsoft Excel and ESRI MapObjects through Visual Basic for Applications (VBA) programming. Six worksheets are included in the Excel front-end: *START*, *H2A Files*, *Commodity Prices*, *Cost Curves*, *Components*, and *OUTPUT*. As this section is an introduction to the capability and operation of HyDS ME, some capability is mentioned, but is not covered in depth.

Spreadsheet Inputs

There are many inputs within the HyDS ME spreadsheets. A subset of the most crucial functionality is listed below.

Commodity Prices Spreadsheet

The feedstock price assumptions are input into the *Commodity Prices* spreadsheet. Figure 13 shows the natural gas price assumptions column. The values highlighted in orange are those used in the computations and can be changed by the user. Various Annual Energy Outlook (AEO) forecast price series are placed in the gray-highlighted columns as references and should not be changed.

Natural Gas Prices						UPDATE ?	TRUE
Year	*Base AEO 2005 Industrial $(2003)/mmbtu*	*High A AEO 2005 Industrial $(2003)/mmbtu*	*Base AEO 2006 Industrial $(2003)/mmbtu*	*High A AEO 2006 Industrial $(2003)/mmbtu*	*Base AEO 2006 Total Consumption (TCF)*	*High A AEO 2006Total Consumption (TCF)*	*Modeled Price $(2003)/mmbtu*
2003	$5.72	$5.72	$5.62	$5.62	22.34	22.34	$5.62
2004	$6.22	$6.22	$6.13	$6.13	22.41	22.41	$6.13
2005	$6.25	$6.25	$8.45	$8.45	22.23	22.21	$8.45
2006	$5.59	$5.59	$7.60	$7.66	22.18	22.15	$7.66

Figure 13 – Commodity Prices spreadsheet functionality

Cost Curves Spreadsheet

HyDS ME can compete up to three different central production technologies and two different distributed production technologies at once. These technologies are selected through a drop down menu available on the *Cost Curves* spreadsheet (Figure 14).

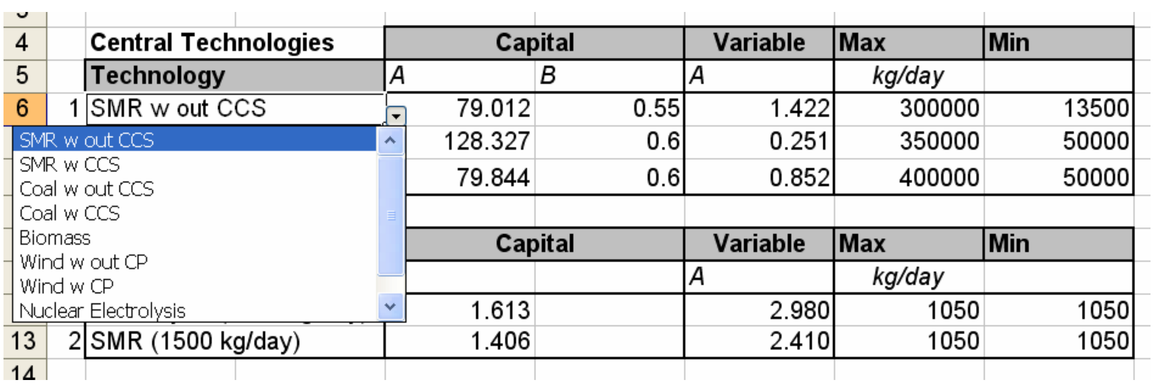

Figure 14 – Production Technology Selection

Additionally, the cost curve assumptions are available in graph format in the *Cost Curves* spreadsheet. These graphs are dynamically updated when new technologies are selected in the above dropdown.

The remaining spreadsheets, *Components*, *Demand*, and *H2A Files* are for advanced use only and are not addressed in this report. The *OUTPUTS* spreadsheet holds all the final results and merits its own section below.

User Interface: Inputs and Operation

The user interface (Figure 15) is initiated by clicking the “PipesPlus” button on the *START* page. The interface consists of a map and a tool bar on the right margin. The map includes the entire United States with state boundaries (black lines), the Interstate Highway System (purple lines), urban areas (UA/UC as black blobs), and existing hydrogen production facilities (yellow triangles).

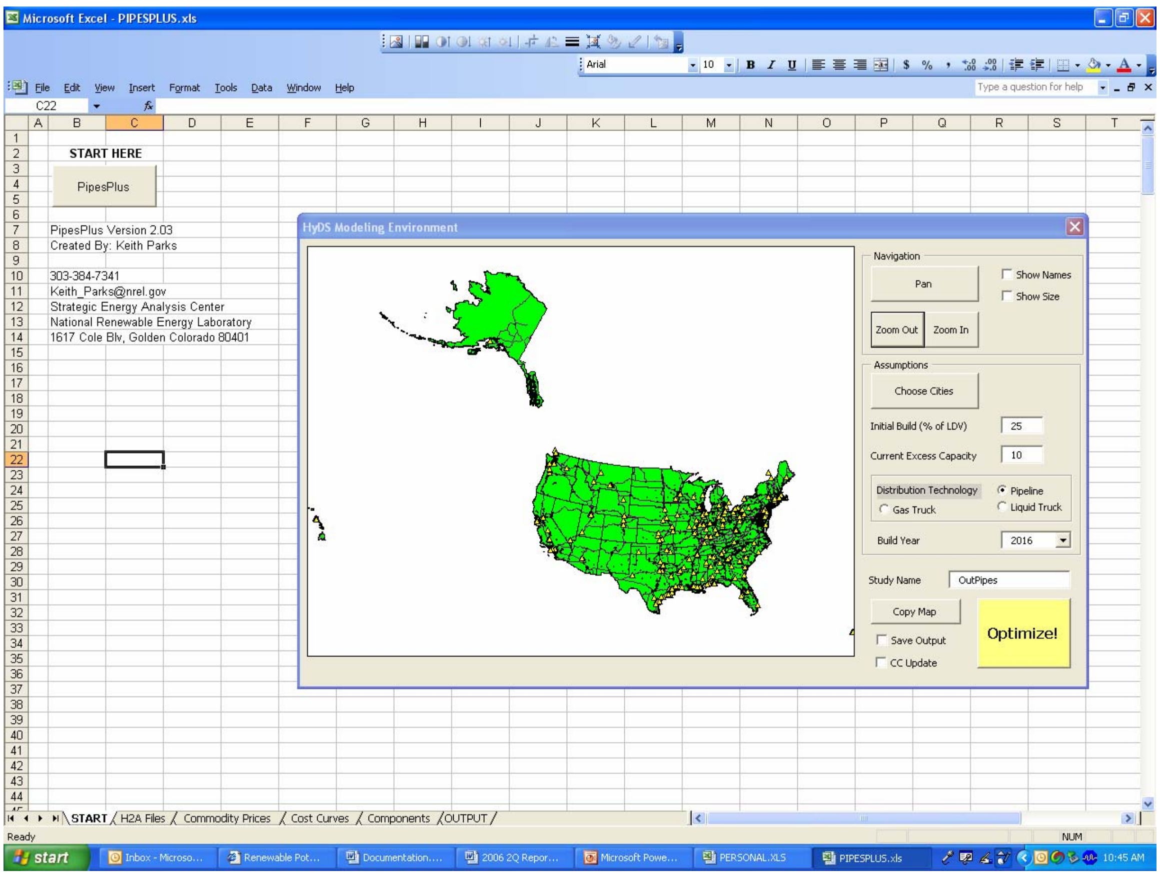

Figure 15 – Opening View of HyDS ME

The user interface toolbar is divided into three parts: *Navigation*, *Assumptions*, and *Execution* (Figure 16).

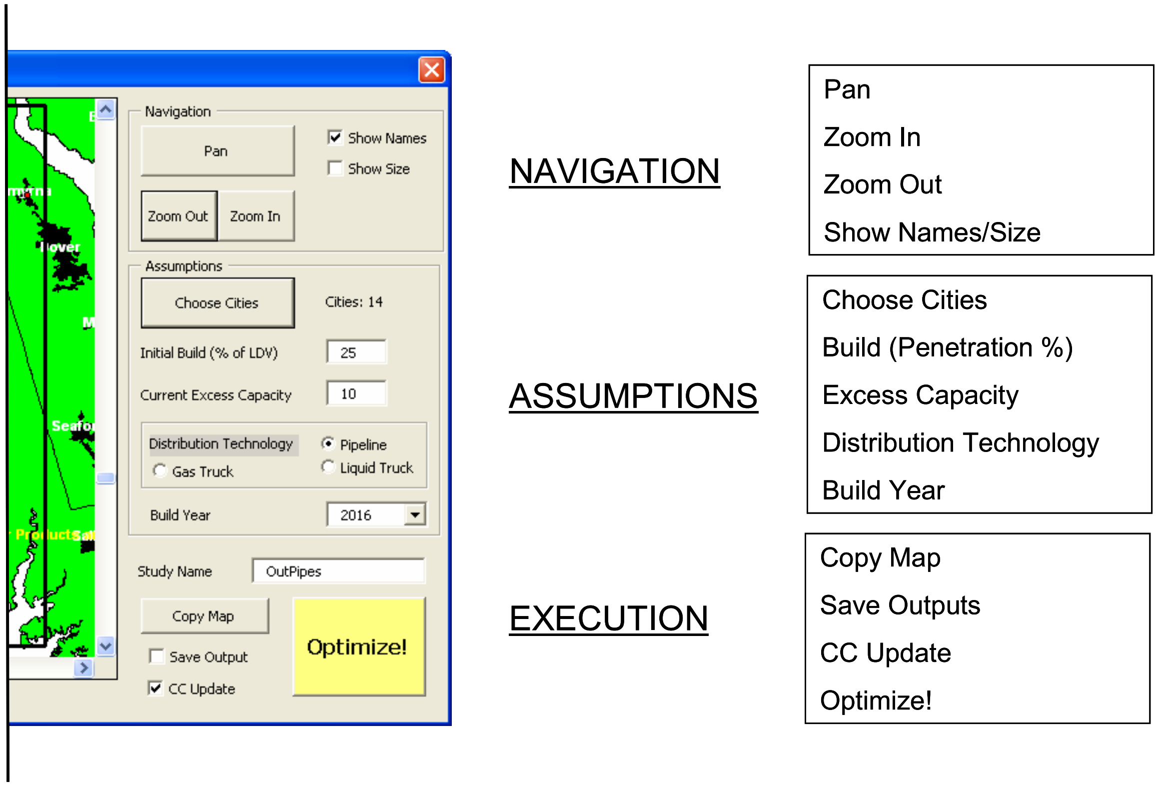

Figure 16 – The HyDS Toolbar

Navigation

The Navigation bar is used to control the display of a study region. This part of the toolbar is used to zoom in on a study region. Press the appropriate button and then either grab or drag over the map to pan, zoom in, or zoom out. These navigation controls are similar to those used in popular mapping software found on the Internet.

The *Show Names* and *Show Size* check boxes will toggle on and off the relative names and populations of the urban areas, respectively. These display features are only useful when zoomed in close to a particular region.

Assumptions

There are several inputs, or assumptions, the user must select or specify to run HyDS ME. These inputs are addressed individually below:

Choose Cities – This button enables the user to select a study region. Drag the left mouse button to draw a rectangle over the map. All cities inclusive of the rectangle (within and touched by) are selected for the study. The right mouse button can be used to select a state by clicking within the state boundary. Multiple states may be selected by right-clicking within additional states.

Initial Build (% of LDV) – This value is the assumed penetration of fuel cell vehicles in the study region expressed as a percentage of total light duty vehicles (household and non-household). The penetration is assumed to be uniform across all urban areas selected.

It is possible to specify different penetrations for different cities, but this functionality is beyond the scope of this introductory description.

Current Excess Capacity – This value is the percentage of existing hydrogen capacity available for the transportation sector. This percentage is applied to every existing facility uniformly. The default value is 10%.

Distribution Technology – The user selects the distribution, or transport and delivery, technology of choice for central facilities. The use of this variable reflects a design choice by the developers to enable a user to isolate one distribution technology impact and cost from another. To compare different distribution technologies, two runs are made, each with the respective distribution technology selected. The least-cost solution between the two distribution options can be inferred through inspection.

Build Year – This value refers to the assumed year in which the infrastructure is built. This value determines the specific H2A Production spreadsheet that is used to price production technologies and the feedstock price paths. The build year is a drop down list of even numbered years. Later years incorporate the assumed cost reducing impact of new technologies.

Execution

The execution portion of the interface toolbar manages the operation, outputs, and assumptions of HyDS ME.

Study Name – Refers to the name of the study spreadsheet into which the run outputs will be saved. A name is required only when the *Save Output* checkbox is activated.

Copy Map – Copies the existing view of the map to the *OUTPUT* spreadsheet.

Save Output – Enables outputs to be copied into an external Excel file as defined by the *Study Name* input box.

CC Update – Enables the dynamic update of the cost curve links to the H2A Production spreadsheets. If any changes are made to feedstock prices, IRR, or any other H2A assumptions within the H2A Production spreadsheets, invoking this update will ensure that these changes are carried into the appropriate HyDS ME worksheets and cells. . This update can take several minutes to complete. If assumptions regarding H2A are not changed, then the cost curves do not need to be updated.

Optimize! – Once all assumptions are input (e.g., selected region, % of LDV), the *Optimize!* Button is clicked. This action invokes the cost curve update (CC Update, if selected), followed by the minimum spanning tree algorithm and finally reporting algorithm.

Interpreting Results- The OUTPUTS spreadsheet

The result of a single run of the HyDS ME can be broken into two parts: The Map and the Supply Curve.

The Map is a spatial representation of the least-cost solution for the region selected. The Map outputs include symbols for distributed and central production, pipeline, and truck transport, as well as the existing state boundaries, hydrogen facilities, and the Interstate Highway System (Figure 17). This output is intended to give the user an immediate geographical view of the hydrogen infrastructure across the region.

The 'Map' demonstrates the extent of central versus distributed production technology, the delivery mode, as well as the state boundaries and Interstate system…

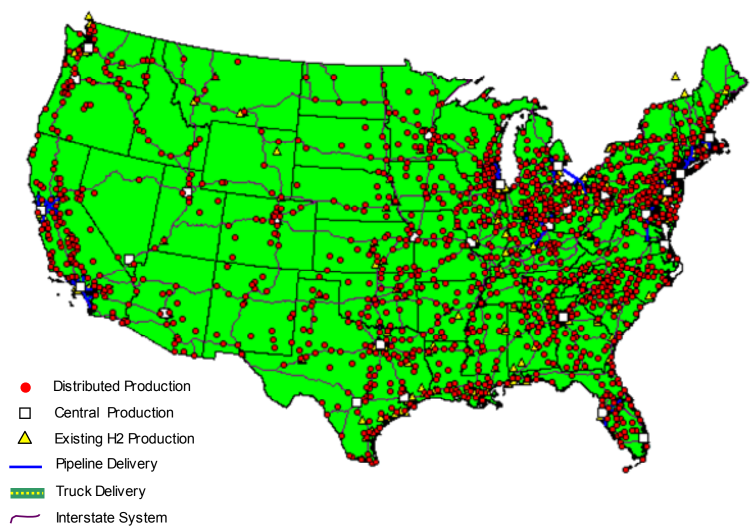

Figure 17 – The Map Output

The cost of hydrogen varies regionally. This variation has less to do with the commodity price of feedstock as with the spatial relationship between large and small urban areas. Given the assumptions regarding production, transport, and delivery, a single urban area is allocated a cost of delivered hydrogen. A neighboring city will, potentially have a different cost due to factors such as demand, distance from production, and urban aerial extent. The costs are sorted from least to most expensive and then plotted against the cumulative hydrogen demand to yield a *regional supply curve* (Figure 18).

The 'Supply Curve' demonstrates the $/kg incremental cost of hydrogen for the entire region. The hydrogen cost for each urban area is sorted from least to most expensive for the entire region. Each city is color-coded depending on its production technology.

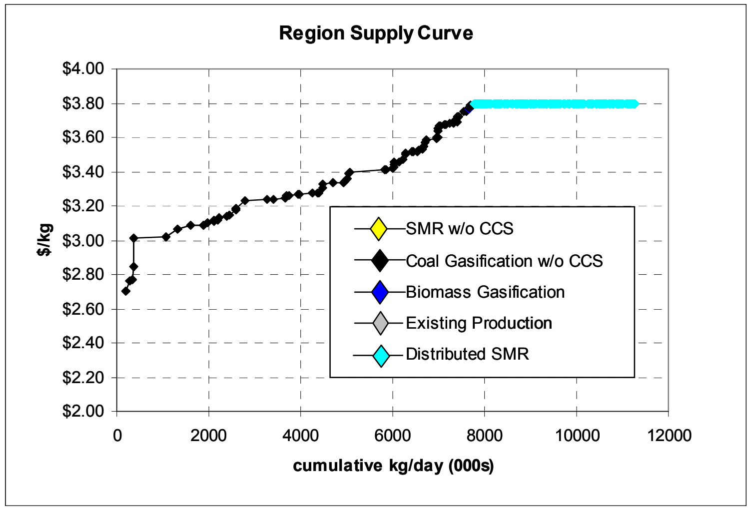

Figure 18 – Regional Supply Curve

The supply curve reflects the spatial diversity of the region, the assumed demand, feedstock prices, build year, and competed technologies.

The map and supply curve are integrally related. They portray the same information in different ways. The following example was created to better explain this relationship. A run was made focused on the Washington/Baltimore region. A natural gas price of $9/MMBtu was assumed as well as a 15% vehicle penetration. Figure 19 displays the two outputs side by side.

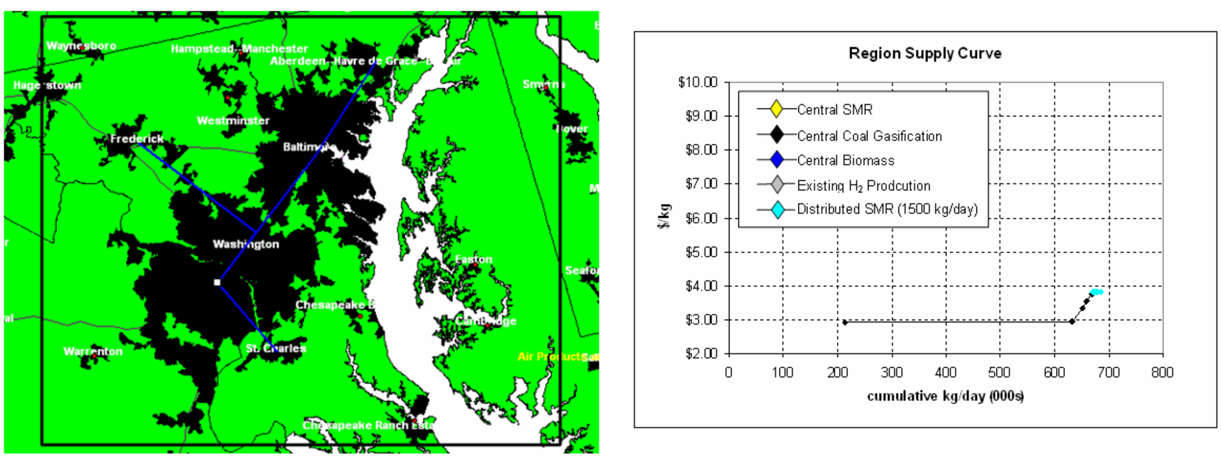

Figure 19 – The Map and Supply Curves Side by Side

First note that Washington and Baltimore are the largest urban markets in the region (Figure 20). They contribute the majority of the hydrogen demand. Since these two large demand centers are near one another, they have nearly the same delivered cost of hydrogen. Central production is shared by both urban centers via a pipeline.

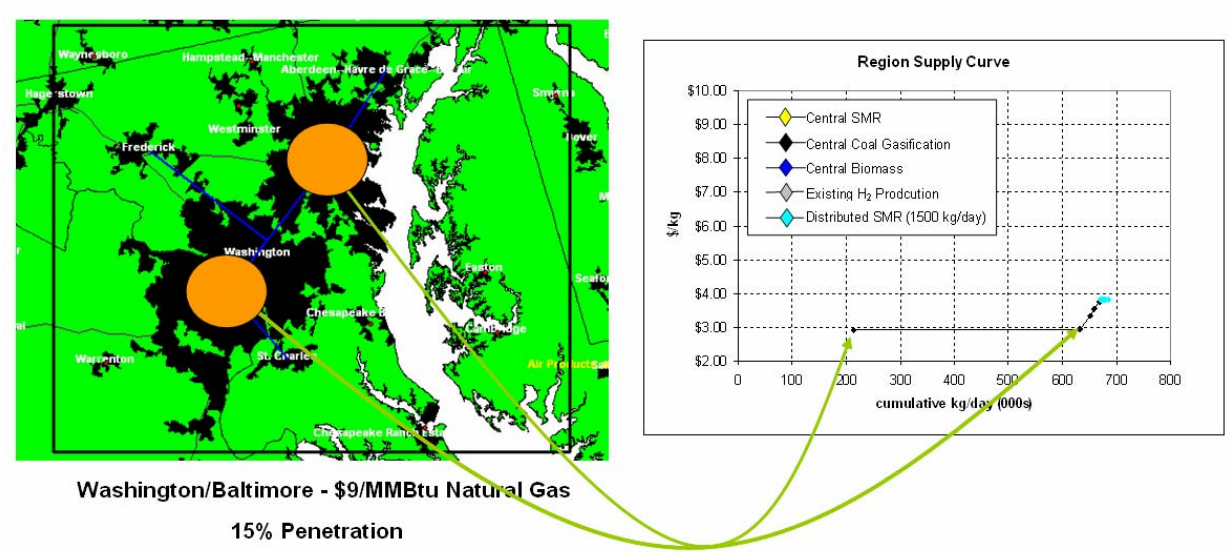

Figure 20 – Washington/Baltimore Share a Central Production Facility

With a nearby central production facility, medium sized markets choose to build to the Washington/Baltimore pipeline (Figure 21). While the incremental cost of transport and delivery drives their total costs up, it is still most cost effective to leverage the Washington/Baltimore urban cluster central production. The blue lines on the map represent the resulting pipeline transport.

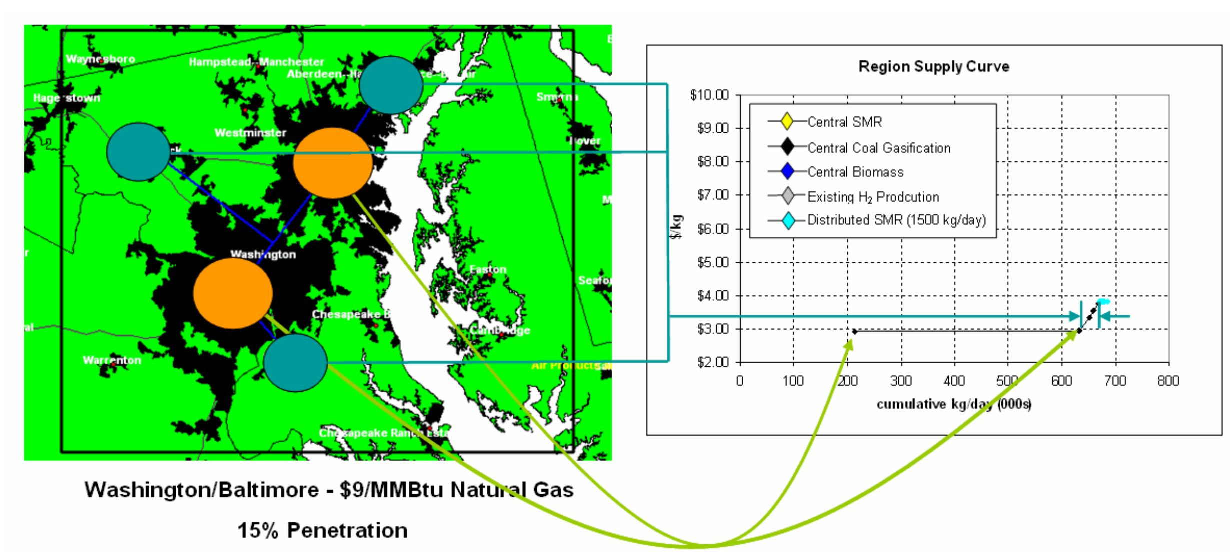

Figure 21 – Medium sized markets link to the Washington/Baltimore pipeline

Finally, outlying small communities opt for distributed production priced at $3.81/kg (Figure 22). Long distance and small demands result in high transport and delivery costs. associated with Washington/Baltimore centralized production. Without some kind of cost sharing, small communities will tend to opt for the cheaper distributed option.

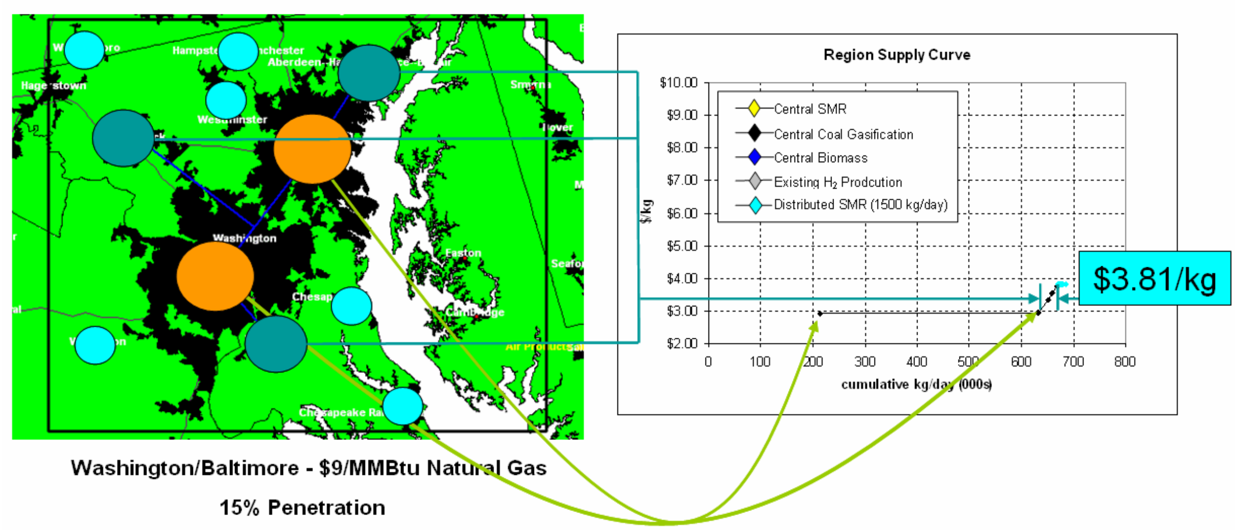

Figure 22 – Small Markets Choose Distributed SMR

Example Runs, Discussion, and Conclusions

For purposes of discussion, two scenarios were run for the United States. Lower 48 region: a Base Case of $6.26/MMBtu[6] and a Sensitivity Case of $12/MMBtu natural gas, both at 15% penetration.

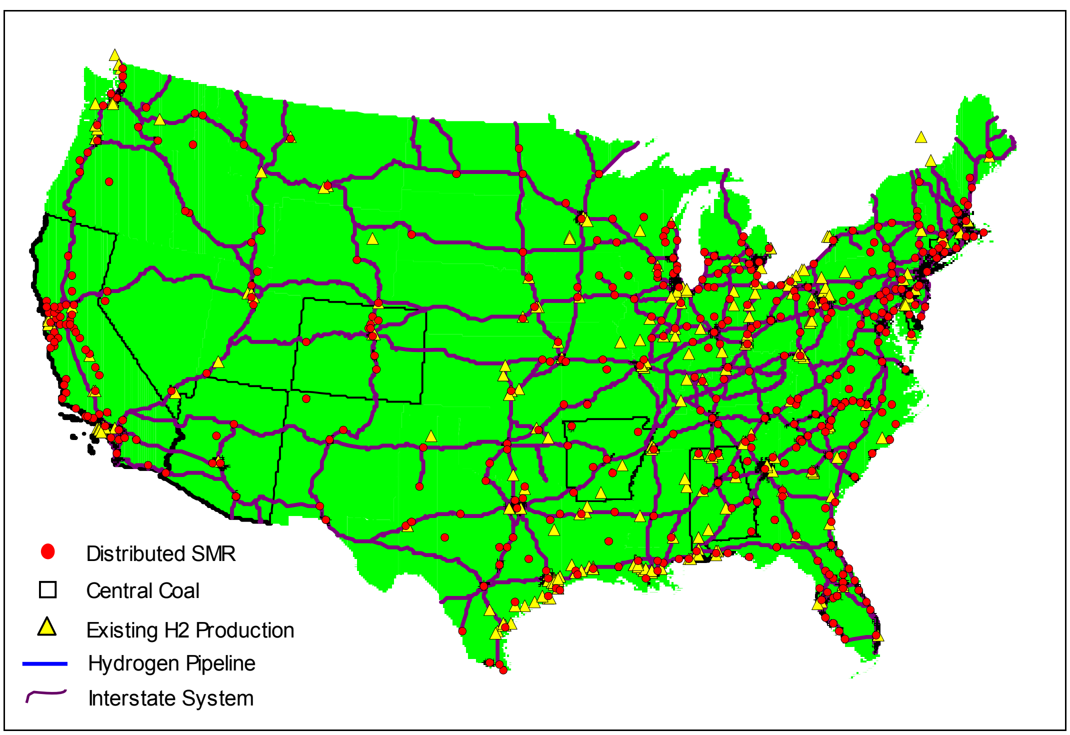

Figure 23 - $6.26/MMbtu Natural Gas Price at 15% Penetration

[6] AEO 2006 Forecasted 2015 High A Natural Gas Price in 2003 dollars. Feedstock forecasts, excluding natural gas, are based on the AEO 2005 High A forecast.

In the Base case (Figure 23), distributed SMR (natural gas) dominates. The cost of 1500 kg/day distributed SMR is $2.78/kg. None of the central technologies can compete with hydrogen production at that cost.

The Sensitivity case (Figure 24) demonstrates a large transition to coal gasification. Twenty seven production centers proximal to the largest demand areas emerge. Communities near these centers leverage the new production via transport pipelines. Communities too small and distant from these centers employ distributed SMR.

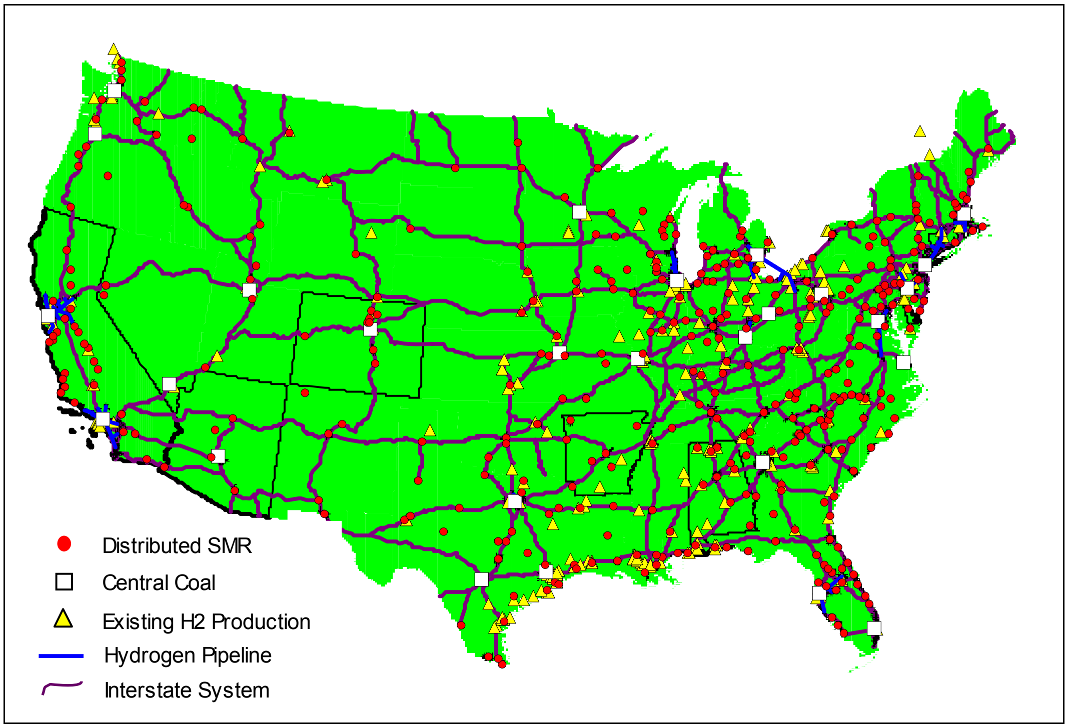

Figure 24 - $12.00/MMBtu Natural Gas Price at 15% Penetration

The corresponding supply curve for the Lower 48 is displayed in Figure 25. The x-axis represents the cumulative hydrogen demand. The y-axis represents the total delivered cost. In constructing the supply curve, the delivered cost for individual urban areas is sorted from least to highest cost. From left to right, the costs rise depending on the central plant size, relative transport costs, and intra-city delivery costs. Eventually, the cost to build and transport/deliver from central production reaches the cost of distributed SMR using $12/mmbtu natural gas ($3.80/kg). Communities then opt for the less expensive SMR rather than assuming ever larger transport and delivery costs associated with central production.

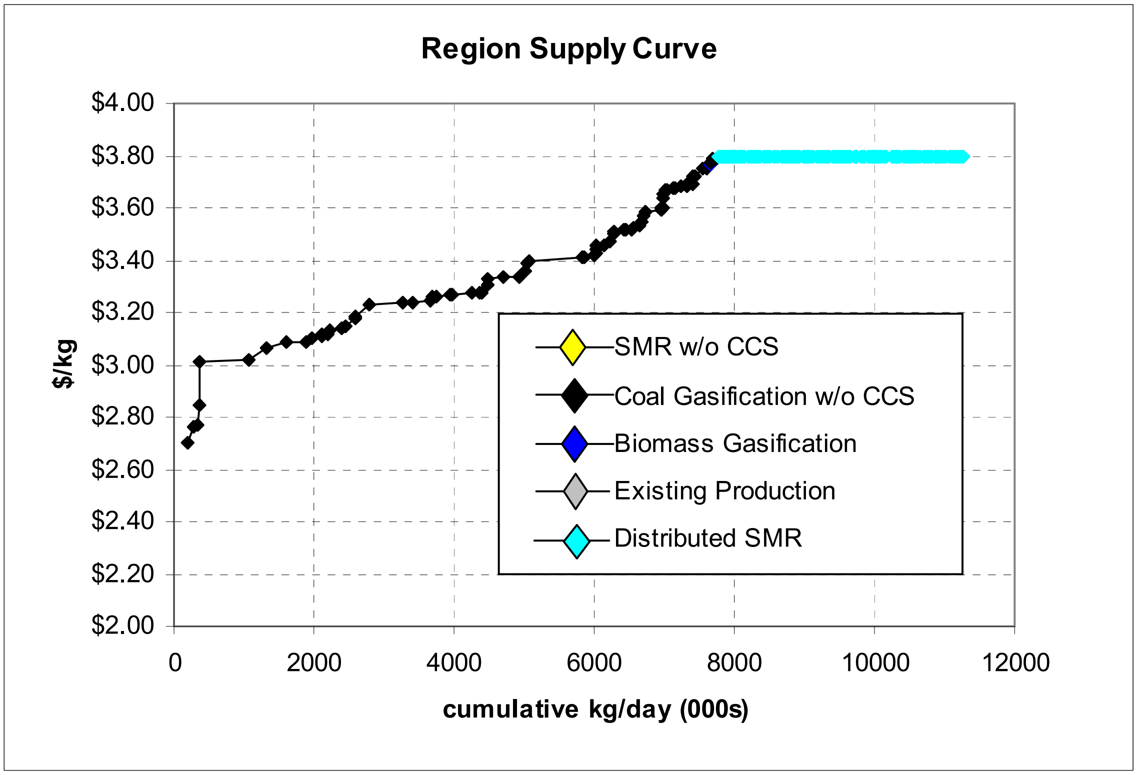

Figure 25 – Hydrogen Supply Curve for the Lower 48 United States at 15% Penetration

In this example, the 82 urban areas that chose central technology represent 18% of the urban areas and 7.8 million kg/day, or 69% of the total demand of 11.3 million kg/day. The remaining 366 urban areas represent 3.5 million kg/day, or 31% of the total demand. That is, a small number of large urban areas comprise the majority of the potential hydrogen demand due to the sheer size of their vehicle populations. The remaining small and more remote communities suffer from their own small market size as well as their relative distance from demand centers.

Conclusions

HyDS ME provides a platform for analyzing hydrogen infrastructure impacts. Geographic characteristics such as vehicle population, aerial extent, size, and relative distances to larger markets are considered. Production, transport, and delivery costs and economies of scale are considered together on a regional basis.

The natural gas price is a major driver in determining least-cost hydrogen infrastructure as it impacts the cost of SMR, a primary distributed technology. For recent EIA gas forecasts ($6.26/MMBtu in 2015), distributed SMR is a least-cost infrastructure choice at 15% and lower penetration of vehicles. When natural gas price is nearly doubled ($12/MMBtu), central technologies may serve up to 69% of the total demand of hydrogen nationwide at 15% penetration. Smaller and more rural urban areas, representing the remaining 31% of demand, suffer from small market size and distance from major demand centers and opt for distributed SMR at this level of penetration.

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